SOLAR X-RAY SPECTROMETER (SOXS) MISSION: OBSERVATIONS AND NEW RESULTS

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Abstract: We present the observations and recently obtained new results from the "Solar X-ray Spectrometer (SOXS)" mission, which was launched onboard GSAT-2 Indian spacecraft on 08 May 2003 by GSLV-D2 rocket to study the solar flares. The state-of-the-art solid state detectors viz. Si PIN and Cadmium-Zinc-Telluride (CZT) were employed that operate at near room temperature (-20 ^{0}C). The dynamic energy range of Si PIN and CZT detectors are 4-25 keV and 4-56 keV respectively. The Si PIN provides sub-keV energy resolution while CZT reveals about 1.7 keV energy resolutions throughout the dynamic range. The high sensitivity and sub-keV energy resolution of Si PIN detector allows measuring the intensity, peak energy and equivalent width of the Fe-line and Fe/Ni-line complex at approximately 6.7 and 8.0 keV as a function of time. We present the results related to Fe line complex obtained from the study of 10 M-class observed by SOXS mission. We found that the equivalent width (w) of Fe-line feature increases exponentially with temperature up to 20 MK but later it increases very slowly up to 30 Mk and then it remains uniform up to 38 MK. We compare our measurements of w of Fe line feature with calculations made earlier by various investigators and propose that these measurements may improve theoretical models. We interpret the variation of both Ep and w with temperature as the changes in the ionization and recombination conditions in the plasma during the flare interval and as a consequence the contribution from different ionic emission lines also varies. Our new findings may help in solving the paradigm of elemental abundances in solar standard model that emerged recently after precise helioseismological measurements.

1. Introduction

The "Solar X-ray Spectrometer (SOXS)" mission (Jain et. al, 2000a, b, 2005) was launched onboard an Indian geostationary satellite namely GSAT-2 on 08 May 2003 by GSLV-D2 rocket. The SOXS Low Energy Detector (SLD) mission (Jain et. al, 2000a, b, 2005) aims to study the high energy and temporal resolution X-ray spectra from solar flares employing solid state detectors viz. Silicon PIN detector for 4 - 25 keV (area 11.56 sq. mm); and Cadmium Zinc Telluride (CZT) detector for 4 - 56 keV energy range (area 25 sq. mm). Details related to the SLD instrumentation, the operation of the detectors, temporal and spectral resolution and the data format were presented earlier by Jain et al., (2005). The SLD payload is designed and developed at the Physical Research Laboratory (PRL) in collaboration with ISRO Satellite Centre (ISAC), Bangalore, and Space Application Centre (SAC), Ahmedabad.

The solar corona exhibits many X-ray lines below 10 keV and in order to improve our current understanding on the X-ray line emission characteristics the synoptic observations at energies below 10 keV are of utmost importance, which may reveal the temperature enhancement during flares of different magnitude. On the other hand, it has been shown by Jain et al (2000a, b, 2005) that iron complex lines (Fe XXV, XXVI) at 6.7 keV and Fe/Ni complex lines at 8 keV appear only during solar flare activity, however, understanding of their emission characteristics require extremely high spectral and temporal resolution observations, may resolve the problem of solar standard model that evolved after the precise abundance measurements from helioseismology instrument (Antia and basu, 2005) and coronal Neon measurement in solar type stars by Jeremy et al., (2005). The high sensitivity and sub-keV energy resolution of Si PIN detector allows the intensity and mean energy of the Fe-line complex at approximately 6.7 keV to be measured as a function of time in all classes of flares.

This line complex is due mostly to the 1s-2p transitions in He-like and H-like iron, Foxx and Foxx respectively, with associated satellite lines. Another weaker line complex at ~ 8 keV made up of emission from He-like nickel and more highly excited Fexxv ions is also evident in the more intense flares (Phillips, 2004, Phillips et. al., 2004). Detailed calculations of emission line intensities as a function of temperature, with provision for different element abundance sets (e.g., photospheric or coronal), are given by the MEKAL/SPEX atomic codes (Mewe et al., 1985a, b, Phillips et. al., 2004) and the CHIANTI code (Dere et al., 1997). These codes also include thermal continuum intensities. These codes are used to interpret the SLD spectral observations in terms of the plasma temperature and emission measure. The centroid energy and width of the iron-line complex at ~6.7 keV, the intensity of the Fe/Ni line complex at ~ 8 keV, and the line-to-continuum ratio are the functions of the plasma temperature and can be used to limit the range of possible plasma parameters. However detailed study of such features of the Fe and Fe/Ni line complexes has not been carried out mainly due to non-availability of spectral observations in the energy range 3 - 10 keV and in particular with high spectral and temporal resolution, which are critically required to measure precisely the line features and plasma parameters. The high spectral and temporal resolution spectra may reveal many unidentified lines as shown by RESIK Bragg crystal spectrometer aboard CORONAS-F (Sylwester et al., 2004). Phillips et al., (2004) carried out study of solar flare thermal spectrum using RHESSI, RESIK and GOES mission data and determined absolute elemental abundances, which however may have subjected to uncertainties due to measurements from three different instruments that were not calibrated by a single common technique. However,

the SOXS mission is providing the X-ray spectra in the desired 4 - 10 keV energy band with improved spectral and temporal resolution. Therefore the purpose of this paper is to study the X-ray emission characteristics of Fe-line feature in solar flares using the high sensitivity and sub-keV energy resolution capabilities of Si PIN detector of SOXS mission. We present the current study of the Fe-line emission as the first results from the observations made by the SLD/ SOXS mission. In section 2 we present the observations made by the SLD payload. Section 3 describes analysis techniques and the results obtained. We discuss our findings in section 4 and conclude in section 5.

2. Observations

The instrumentation of the SLD payload, its in-flight calibration and operation has been described by Jain et al. (2005). However, a brief description of the experiment is as following. The SOXS consists of two independent payloads viz. SOXS Low Energy Detector (SLD) and SOXS High Energy Detector (SHD) payloads. The SLD payload is functioning satisfactorily onboard the GSAT-2 spacecraft and so far more than 300 flares of importance greater than GOES C1.0 have been observed. The spectral resolution revealed by Si detector is 0.7 keV @ 6 keV and 0.8 keV @ 22.2 keV, which is better over the earlier detectors used for solar flare research in this energy range. However, spectral resolution achieved from CZT detector is poor i.e., almost 1.7 keV but it remains stable throughout its dynamic energy range of 4 – 56 keV. Further their temporal resolution capabilities are also superb however we designed for 100 ms during flare mode in order to achieve feasible energy spectrum.

The temporal data i.e., intensity (counts/s) as a function of time is revealed in four energy band viz. 6-7 keV (L1), 7-10 keV (L2), 10-20 keV (L3) and 4-25 keV (T) by Si detector, while in five energy bands by CZT detector viz. 6-7 keV, 7-10 keV, 10-20 keV, 20-30 keV and 30-56 keV. In Table I we show the flare events analyzed by us to study the X-ray spectral evolution of Fe-line feature in the flare plasma. We selected eight flares of *GOES* importance class M for the current study as first results. However in preview to goal of studying Fe-line feature we use data from Si detector only for the current investigation.

2.1 *Temporal Mode*:

In Figure 1 we show the temporal mode observations i.e. light curves of 31 October 2004 flare in four energy windows of Si detector. The time resolution for temporal and spectral mode observations during quiet period is 1 s and 3 s respectively but during flare it is 100 ms for both

temporal and spectral modes. The intensity (counts/s) of the light curve shown in Figure 1 is 20 s moving average of the 100 ms observed data. It may be noted that the flare is gradually rising and long enduring.

Table I

SLD/SOXS Flare events considered for investigation

| S. No.	Date	Time UT			GOES	Active Region	
		Begin	Peak	End	Class	Location	NOAA
1.	30 Jul 2003	0407	0409	0428	M2.5	N16 W55	10422
2.	13 Nov 2003	0454	0501	0510	M1.6	N04 E85	10501
3.	19 Nov 2003	0358	0402	0419	M1.7	N01 E06	10501
4.	07 Jan 2004	B0355	0400	0433	M4.5	N02 E82	10537
5.	25 Mar 2004	0429	0438	0507	M2.3	N12 E82	10582
6.	25 Apr 2004	0528	0536	0558	M2.2	N13 E38	10599
7.	14 Jul. 2004	0518	0523	A0525	M6.2	N12W62	10646
8.	14 Aug 2004	0413	0414	0432	M2.4	S13 W30	10656
9.	31 Oct 2004	0526	0531	0546	M2.3	N13 W34	10691
10.	25 Aug 2005	0436	0439	0452	M6.4	N07E78	10803
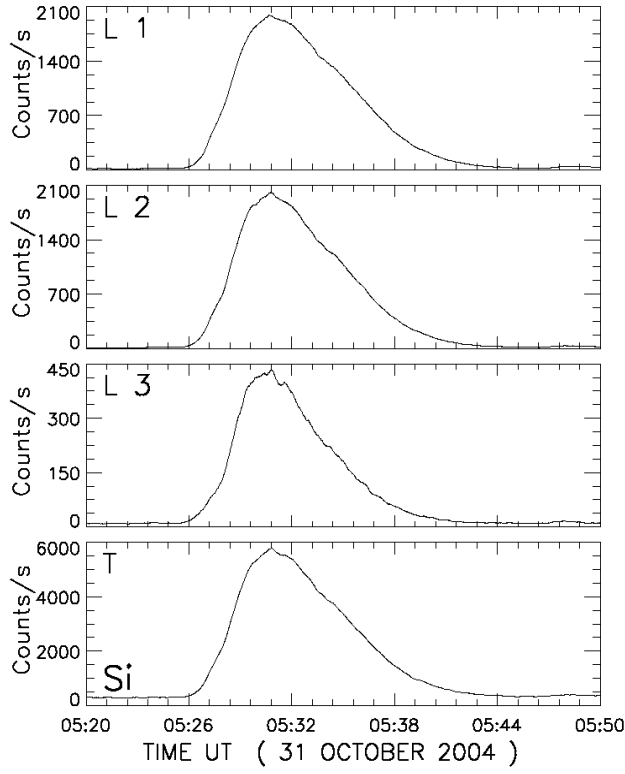
Figure 1: Light curves of 31 October 2004 solar flare as recorded in L1, L2, L3 and T energy bands (see text) of Si detector of SLD/ SOXS mission
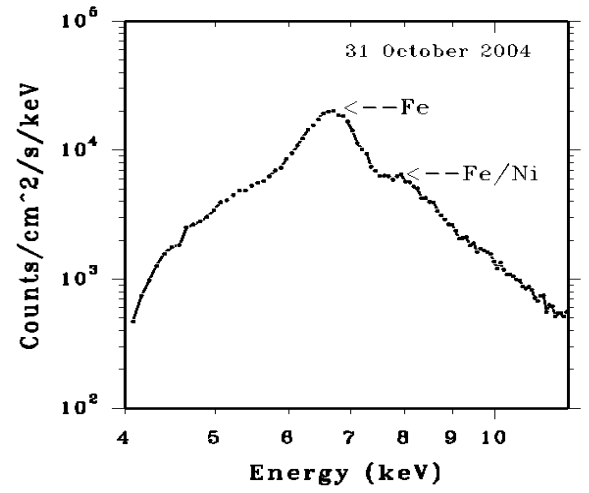

Figure 2: Count Spectra from Si PIN detector for 31 October 2004 flare at 05:30:59 UT. Note Fe and Fe/Ni line features.

2.2. *Spectral Mode*:

The energy region 4 - 15 keV in solar flare X-ray spectrum is of great importance in inferring the properties of the hottest parts of the thermal plasma created during a solar flare. It contains emission lines of highly ionized Ca, Fe, and Ni atoms and a continuum that falls off steeply with increasing energy. In this context, SLD is the first payload, which has dedicatedly dynamic energy range 4 - 25 keV to study the line emission and continuum with sub-keV spectral resolution. This is achieved by employing Si PIN detector as described in the preceding section.

The energy spectrum, intensity (counts/s) as a function of energy at a given time, in the energy range 4 – 25 keV distributed over 256 channels with channel width of 0.082 keV, obtained from the instrument is in the form of count spectra, The Si detector's count spectra at the peak time of 31 October 2004 flare is shown in Figure 2. The low intensity below 6 keV is due to aluminum plus kapton filter mounted on the detector head to cut the X-ray photons up to 4 keV and electrons up to 300 keV falling in the line-of-sight of the detector (Jain et al., 2005). It may be noted that in Si count spectra the Fe and Fe/Ni lines are unambiguously visible at ~6.7 and ~8 keV respectively. The count spectra are de-convoluted over the instrumental response to obtain the photon spectra, which are indeed useful to study the X-ray line and continuum emission.

3. Analysis and Results

The raw data for temporal and spectral mode observations is first corrected for any spurious or false flare as well as for pre-flare background (Jain et al., 2005). The spectrum at a given time is made by integrating the high cadence (100 ms) spectra over an interval of 30 to 100 s period. The photon spectrum is produced by de-convolution of the count spectrum over the instrumental response. The photon spectra are used to study the evolution of Fe and Fe/Ni lines in a given flare as a function of time. Each photon spectra is formed by integrating the several spectra observed at the cadence of 100ms or 3s interval.

3.1 X-RAY EMISSION FROM Fe-LINE:

In order to study the Fe and Fe/Ni line emission it is rather more important to study their evolution with the flare development i.e., as a function of temperature because the line emission and its intensity vary with temperature and emission measure (Phillips, 2004). Shown

in Figure 3 is a sequence of photon spectra of 31 October 2004 flare in the energy range 5 to 12 keV. The sequence shows evolution of the Fe and Fe/Ni lines as a function of time. It may be noted from this figure that the peak intensity, peak energy and area under the curve of the lines vary over time. In fact the plasma temperature and hence emission measure vary over time and these factors mainly controls the shape of the line. However, non-thermal contribution also plays role but in this paper we consider only temperature and emission measure as important parameters. .

The Fe line feature is here defined as the excess above the continuum, as observed by Si spectrometer with spectral resolution (FWHM) ≤ 0.7 keV, in the energy range 5.8 - 7.5 keV (Phillips, 2004). It may be noted from the temporal evolution of this line shown in Figure 4 that Fe-line features including the peak energy and intensity vary over the flare evolution, which suggests that the abundance and peak energy of the emission line vary as a function of temperature. In this paper we intend to investigate the variation in peak energy of the Fe-line feature by Gaussian fit, which lead us to measure the central peak energy for a given spectra. We analyzed 10 to 27 spectra, for each flares under study, depending on the duration of the flare. SOXSoft package (Patel and Jain, 2005) is the software package used for data analysis. SOXSoft is specially developed for SOXS mission for data processing and spectra formation.

Once the photon spectra formed (cf. Figure 4) we undertake their analysis for deriving plasma parameters such as temperature, emission measure and spectral index using SOXSoft spectra fit program. This program takes main routine from Solarsoft where Mewe and Chianti codes can be used to derive the plasma parameters. In order to fit the spectra in the energy range between 5 and 15 keV and particularly the Fe-lie feature by isothermal plasma we use Chianti code because thermal continuum from it is within 1% of the detailed calculations of Culhane ((1969) and the approximation of Mewe et al., (1985a). We use the best-fit to the line feature based on the minimum reduced χ^2 (difference counts). In order to derive the line parameters such as the peak energy (Ep), net area and gross area under the curve and equivalent width we subtracted the continuum contribution to the spectrum. The temperatures are derived from the continuum in the energy range 9.5 to 16 keV using Chianti best-fit code.
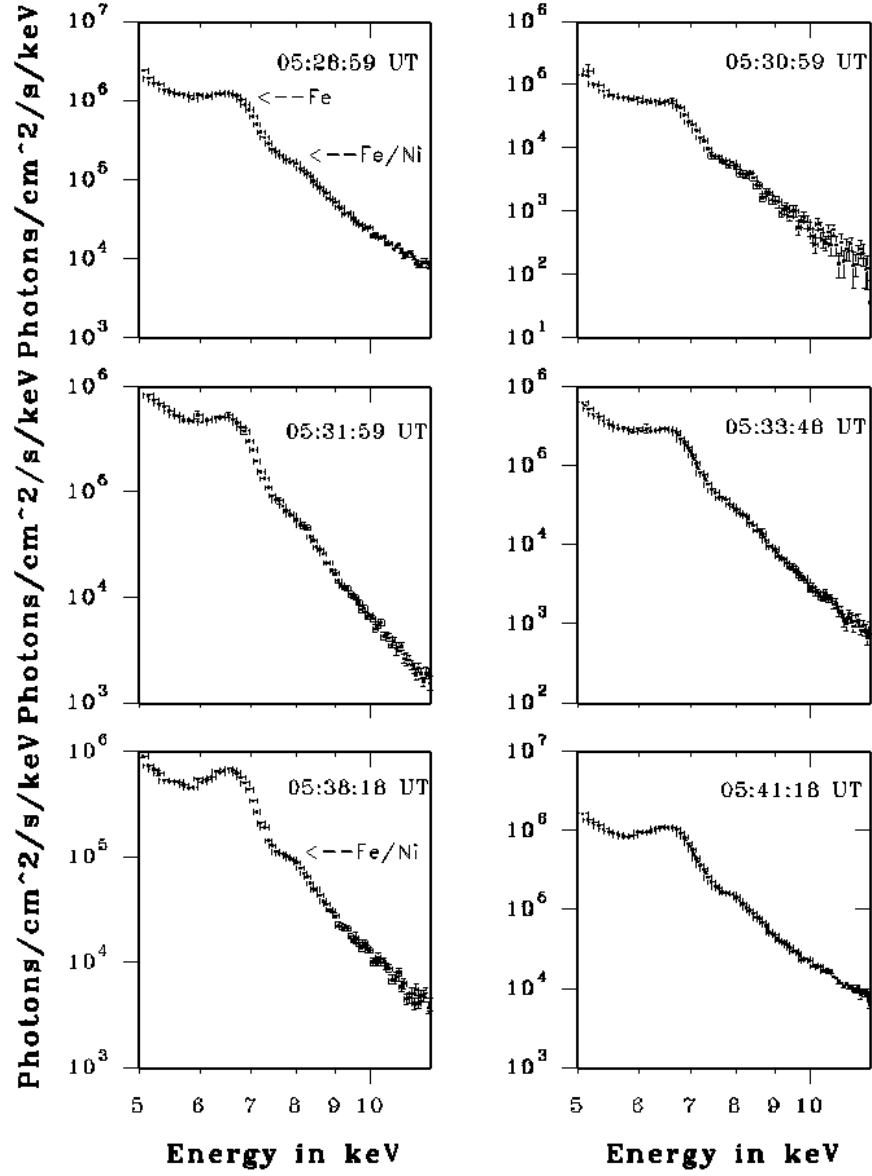
Figure 3: Sequence of X-ray photon spectrum in the energy range 5 – 12 keV of 31 October 2004 flare showing evolution of Fe and Fe/Ni line features. X-axis error bar is channel width of 0.082 keV, while Y-axis error bar is ± 1σ of the photon flux in the given channel.

3.1.1 *Evolution of Temperature and Emission Measure*:

Temperatures are derived from the continuum part in the photon spectrum. In Figure 4 we show a best-fit of photon flux from Chianti code of isothermal plasma temperature and emission measure for the energy range generally between 9.5 and 16 keV for a photon spectra of 31 October 2004. The temperature and emission measure measured for this spectrum are 29.3 MK and 1.3e49 cm^{-3} respectively. The isothermal fit by Chianti code using Solarsoft is accepted if reduced χ^2 < 5. For example the residual counts for the continuum fit for a χ^2 of 1.55 (Figure 4) are shown in Figure 5. In this way, we obtain temperature and emission measure values for each photon spectra of a given time of the flare. We studied almost 10 to 27 photon spectra for each flare depending upon its duration.

3.1.2 *Peak Energy of Fe-Line Features*:

The thermal component in Si PIN spectra is observed to have a prominent broadened emission line features at 6.7 keV and a less intense line feature at 8 keV indicating high plasma temperatures. The 6.7 keV features corresponds to a group of emission lines due to Fe xxv, associated dielectronic satellites of ions from Fe xix to Fe xxiv, and fluorescence-formed lines of Fe ii, and a second group due to Fe xxvi (Lyα) lines and associated satellites. The Fe xxv lines are excited at electron temperatures $T_e \geq 12$ MK, while the Fe xxvi lines are excited at $T_e \geq 30$ MK (Phillips, 2004). This line complex is referred in this paper as the Fe line feature. Thus we may conclude that the Fe-line feature is made up of many individual lines each having its own temperature dependence. Their contribution to the total emission of Fe line feature will therefore change as the temperature of a solar flare plasma changes in both space and time. This results in changes to the energies of the Fe-line feature, as defined by the energy of the peak intensity (E_p). Changes in E_p, if large enough, therefore provide a possible useful temperature diagnostic.
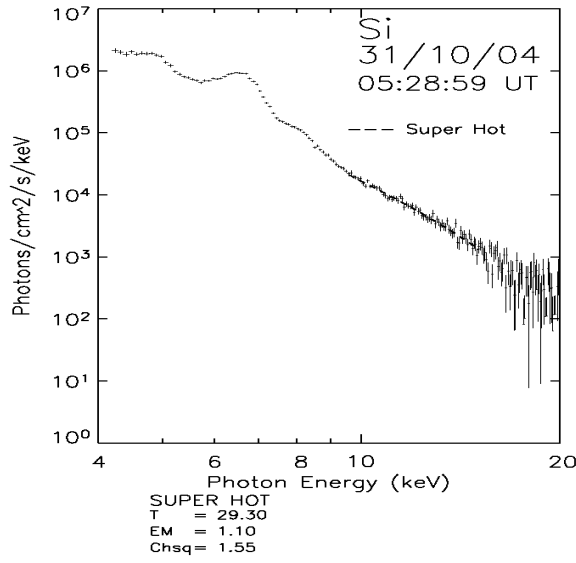
Figure 4: The X-ray photon spectra of 31 October 2004 at 05:28:59 UT. Note the 9.5 – 16 keV continuum fit by isothermal plasma temperature and emission measure. X-axis error bar is channel width of 0.082 keV, while Y-axis error bar is ± 1σ of the photon flux in the given channel.
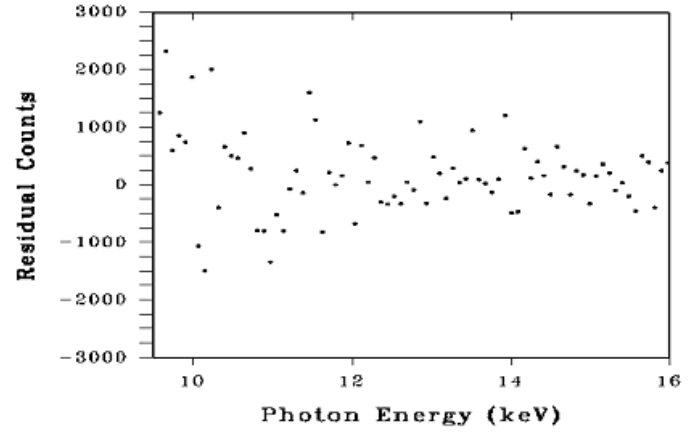
Figure 5: The residual (difference) counts of isothermal plasma continuum fit (cf. Figure 4).

In Figure 6 we show the variation of peak energy (E_p) as a function of temperature of Fe-line feature. We measured E_p for each photon spectra at a given time of a flare for which temperature was derived from continuum. A total 108 spectra from all 8 flares were analyzed to measure E_p. Later, in order to get better statistical confidence, we distributed the108 E_p measured values in the interval of 1 MK according to their respective spectra temperature. For example, all E_p measurements from the spectra falling in the temperature range between 9.6 and 10.5 MK were averaged to mean value and also a standard deviation (σ) was obtained. This mean E_p value is shown with ±1σ.at mean temperature 10 MK. The E_p for each photon spectra of each individual flare was derived by line parameter software analysis of Soxsoft that employs Chianti code to derive plasma parameters. The peak energy (E_p) is the channel having peak intensity in the integrated spectra. The channel width is 0.082 keV in Si PIN spectrometer and therefore measurement of peak energy varying between 6.4 and 6.8 keV as a function of temperature could be possible with better precision. Figure 6 shows that E_p increases with temperature, which is in agreement to Phillips (2004), and Oelgoetz and Pradhan (2004).
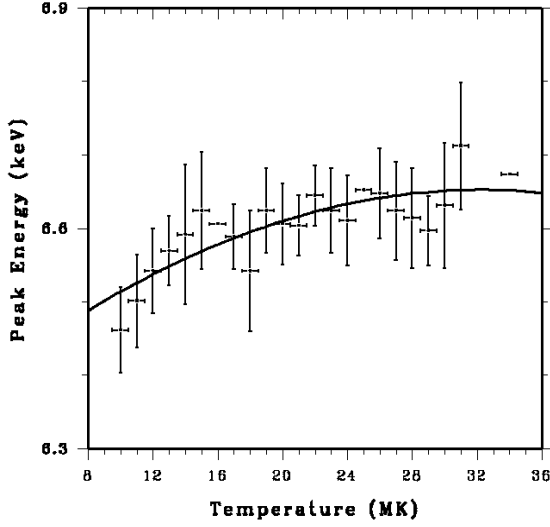
Figure 6: Variation of peak energy (E_p) of Fe-line feature as a function of temperature. Horizontal bars indicate temperature interval of ± 0.5 MK over which the mean Ep is derived. Vertical bars represent ±1σ error in $E p$ measurements.
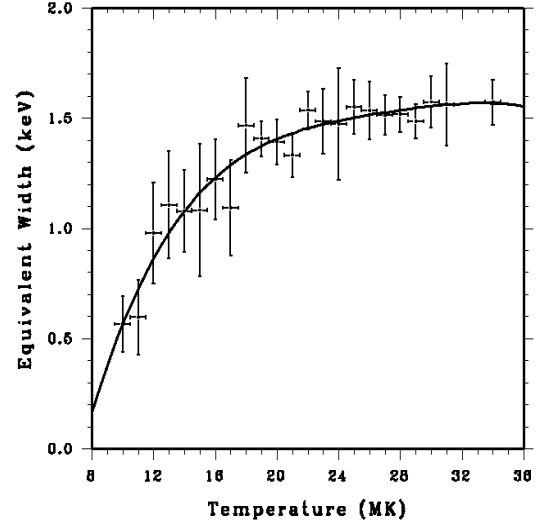
Figure 7: Equivalent width (*w*) as a function of temperature. Horizontal bars indicate temperature interval of ± 0.5 MK over which the mean *w* is derived. Vertical bars represent ±1σ error in *w* measurements.

3.1.3 *Equivalent Width of Fe-line features in Flare Plasma*:

The observations of the Fe line and Fe/Ni line features and neighboring continuum offer a means of determining the iron abundance A_{flare}(Fe) and similarly the nickel abundance A_{flare}(Fe/Ni) during flares. The thermal plasma during flares is located in the coronal loop structures typically 10^4 km above the photosphere. On a chromospheric evaporation picture, this plasma is formed from the chromosphere and therefore should reflect the chromospheric composition. Fludra and Schmelz (1999) and Phillips et al., (2003) showed that elements with a variety of first ionization potential (FIP) are in ratios that are characteristics of the corona i.e., with low-FIP (FIP ≤ 10 eV) elements enhanced by a factor of 3 or 4 but with high-FIP elements approximately the same or depleted by a factor up to 2 compared with photospheric abundance. However elements enhancement might depend upon flare intensity and duration. Thus study of large number of variety of flares is important. Further Fe and Ni both are low-FIP elements and therefore SLD/SOXS observations of Fe and Fe/Ni line features in contrast to neighborhood continuum may allow to determine abundance of Fe and Fe/Ni in flare plasma.

A measure of the Fe-line feature's intensity with respect to the continuum is provided by the equivalent width (w), measured in keV, which can be determined from Si/SLD spectra. In order to get better statistical confidence we carried out a detailed study of the equivalent width (w) by analyzing all 10 M-class flares under current investigation. Alike the peak energy (E_p) we derived w from each photon spectra of a given time of the flare for which temperature was measured from continuum. A total 140 photon spectra from 10 flares were analyzed to measure the w. Later, similar to E_p, in order to get better statistical confidence, we distributed the 108 measured values of w in the interval of 1 MK according to their respective spectral temperature interval (cf. 3.1.2). For example, all w measurements from the spectra falling in the temperature range between 9.6 and 10.5 MK were averaged to a mean value and also a standard deviation (σ) was obtained. This mean w value is shown with $\pm 1\sigma$ at mean temperature 10 MK and so on. Shown in Figure 7 is variation of the mean w with temperature, which, shows an exponential rise of w until 20 MK and later slowly up to 35 MK. However it may be noted from this figure that w remains almost between 2.8 and 4.3 keV in the temperature range $20 - 35$ MK but peak is around 40 MK, which remains until 45 MK. A decreasing trend in w begins after 45 MK. The decreasing trend towards higher temperature is seen for the maximum temperature 54 MK that measured by us in the flares under current investigation.

4. Discussion

It is well established that during the flare interval the plasma is not at one temperature rather it varies as a function of time (Feldman et al., 1995). However, in addition to this fact, our study show temperature does not vary smoothly rather fluctuates in general during the whole flare interval and rapidly in particular during rise phase. This fluctuation in flare plasma temperature (T_e) affects the ionization state and thereby as a consequence of it we observe variation in peak energy (E_p) and equivalent width (w) of the Fe-line emission. Our photon spectral observations from the 10 flares under study show minimum critical temperature required for Fe-line feature to be visible is 9 MK. With increase in temperature viz. $9 < T_e < 30$ MK He-like Fe-lines and satellite ($6.4 - 6.7$ keV) are most intense. Our Si detector begins spectral observations from 4 keV and therefore question to observing Ca-line feature around 3.8 keV does not exist. However the observed increase in T_e unambiguously represents change in peak energy because of excitation of different principal lines of He-like Fe xxv, satellites and resonance lines in agreement to earlier calculations (Gabriel, 1972, Boiko et al., 1978, Doschek et al., 1981, Feldman et al., 1995, Kato et al., 1997, Phillips, 2004).

The strength of Fe-line feature above the continuum i.e. equivalent width (w), which gives an estimate of $A_{flare}(Fe)$ in terms of the coronal abundance, also found varying over the T_e of the flare plasma. However an exponential rise in w is seen up to 20 MK and then later it slows down to remain between 2.8 and 4.3 keV. The equivalent width measured by us is in close agreement to Phillips (2004) though significant deviation exists in the temperature range of 25 – 50 MK. This motivated us to compare with that calculated earlier by Raymond and Smith (1977), Sarazin and Bahcall (1977), Rothenflug and Arnaud (1985) and Phillips (2004) as shown in Figure 8. It may be noted from this figure that our measured values of w are significantly higher than Raymond and Smith (1977), referred as RS77, and Sarazin and Bahcall (1977), referred as SB77, and Rothenflug and Arnaud (1985) referred as RA85 in the temperature range 14 to 54 MK. Calculations of w from Phillips (2004), referred as P04, appear close to our measurements.

Rothenflug and Arnaud (1985), Phillips (2004) and Oelgoetz and Pradhan (2004) calculated equivalent width (w) of the different ionic participations of Fe-line feature and showed that how it varies with temperature for each individual ionic line. The w of Fexxv line is higher than Fexxiii, Fexxiv and Fexxvi up to 100 MK. Above 100 MK emissions from Fexxvi becomes stronger and the total w is dominated by this emission. However, contribution to w from Fexxii, Fexxiii and Fe xxiv almost stops around 21, 35 and 115 MK respectively. Therefore, in the temperature range of 9 – 34 MK for the flares studied in this investigation major contribution for w may be considered from these ionic emissions and Fexxv. However, a little contribution from Fexxvi may be considered when temperature exceeds 30 MK. The difference in calculations by earlier investigators may be due to selection of codes. Our experimental measurements of equivalent width as well as of peak energy and their variation over temperature may help to improve theoretical calculations. Further improved understanding of Fe abundance may help in resolving the problem of elemental abundances in solar standard model.

5. Conclusion

The Si PIN detector of the SOXS Low Energy Detector (SLD) payload provides a unique opportunity to study the Fe-line and Fe/Ni line features in great details. In this paper we carried out study of Fe-line feature in order to investigate the variation of peak energy (E_p) and equivalent width (w) as a function of temperature of the flare plasma. We found that peak

energy of Fe-line feature varies from 6.4 at 9 MK temperatures to 6.7 at 30 MK. More interestingly, equivalent width (w) rises exponentially up to 20 MK and then slowly to reach to peak ~4.5 keV at 40 Mk. We interpret the variation of both E_p and w with temperature as the changes in the ionization and recombination conditions in the flare plasma during the flare duration and as a consequence the contribution from different ionic emission lines also varies. Our measurements of w are compared with previous calculations and found that they are close to the results of Phillips (2004). It is proposed that our measurements of w may help in improving theoretical calculations and elemental abundances in solar standard model.
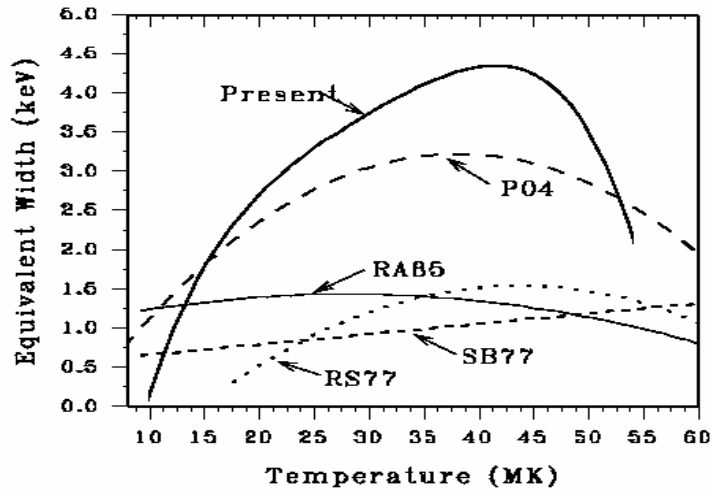
Figure 8: Comparison of our measured values of equivalent width (w) with previous results from RS77 (Raymond and Smith, 1977), SB77 (Sarazin and Bahcall, 1977), RA95 (Rothenflug and Arnaud, 1985) and P04 (Phillips, 2004).

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